A STUDY OF THE FEASIBILITY AND PROBABLE NECESSITY OF PRORATING WATER FLOOD OIL PRODUCTION FROM RESERVOIRS OF INTERGRANULAR POROSITY

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by

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TABLE OF CONTENTS

FOREWORD

In evaluation and appraisals of oil property, it has been said that a competent man must be a combination geologist, lawyer, engineer and accountant. Perhaps the fullest answer to the problem of whether proration should be applied to water flood operations may require mastery of additional fields such as economics and political science. Resolving the immense complexity of physical and economic relations involved in the question could well occupy the time and talent of a staff of specialists in all these fields for a prolonged period. Early in this investigation it was recognized that limitations imposed by manpower and experience would compel the acceptance of an ultimate objective for this thesis that would be less than a final and irrefutable settlement of the question. It is hoped that the factors discussed may shed some light without generating too much heat in areas where a sense of national responsibility may encourage others to pursue the subject further.

The guidance and encouragement of Professor H. G. Botset, Head of the Petroleum Engineering Department and Professor P. F. Fulton, both of the University of Pittsburgh, is gratefully acknowledged. Assistance was also received from many individuals in the oil industry. Appreciation is expressed to the U. S. Naval Postgraduate School, Monterey, California for their sponsorship of the Petroleum Logistics Curriculum at the University of Pittsburgh under which this work was performed.

I. INTRODUCTION

A. Background of Water Flooding and Proration

Methods of producing crude oil may be divided into two broad categories popularly known in the industry as primary production and secondary recovery. Following the discovery of a field, oil is initially produced by natural displacement resulting from the energy of dissolved gas, expanding gas cap or active edge and bottom water incursion, during the period of primary production part of which is usually "flush" or flowing production, followed by artificial lift. Oil fields exhauted by these natural producing mechanisms may still contain large quantities of oil which can be recovered by means of secondary recovery. The technique of injecting gas or water into the reservoir to displace some of the residual oil, which can no longer produce by primary means alone, is broadly known as secondary recovery. The application of secondary recovery methods under modern production practices is frequently commenced prior to complete exhaustion of primary production. In such cases where fluids are injected, the operation is sometimes classified as pressure maintenance. At times it is difficult to draw a sharp line between the primary production phase and secondary recovery operations. The definition of secondary recovery used by the American Petroleum Institute[1] is:

> Recovery by any method (natural flow or artificial lift) of that petroleum which enters a well as a result of augmentation of the remaining native reservoir energy (as by fluid injection) after a reservoir has approached its economic limit by primary-recovery methods.

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[1] References are listed in the Bibliography.

Secondary recovery operations produce the most notable results where primary production has been inefficient. As primary production methods improve the need for secondary recovery diminishes.

Water flooding is one of the two common fluid injection methods of secondary recovery. The following is a good description of water flooding taken from a Texas Railroad Commission hearing:[2]

> Water flooding is a method of secondary recovery whereby water is injected into a depleted oil reservoir through numerous injection wells for the purpose of driving oil left in the formation to the producing wells, thereby recovering large quantities of oil, which could not otherwise be recovered. Water flooding is normally carried out on what is known as a five spot plan. That is a grid pattern with alternate and offset rows of input and producing wells. The pattern consists of having one producing well in the center of a square bounded by four injection wells and likewise each injection well is in the center of a square bounded by four producing wells. In many cases, in fact most cases, it is even necessary to drill new producing wells from which to obtain the increased oil recovery.

In addition to the five spot pattern, the plan of the pattern may be designed to take advantage of the structure of the field.

Proration is one of several conservation remedies, the others being unit operations, regulation of imports and constructive marketing. The meaning of proration is best gained by a brief review of the history of the evolution of modern conservation practices which is well covered in the literature.[3,4,5]

The fluid nature of oil and gas is responsible for a conflict of interest which necessitates regulated production in order to prevent waste of natural resources. Early courts recognized that oil and gas were a part of the mineral wealth inherent in the land. The land or lease owner possessed the right to drill wells and reduce any oil or gas in the ground to possession. Under the concept of the "law of capture," oil and

gas, in whatever quantity that could be produced, belonged to whoever brought it to the surface. Failure to pursue a vigorous policy of drilling and exploitation meant that oil could be forever lost to a more enterprising neighbor. As a natural outcome of the race to exploit newly discovered fields, huge quantities of oil periodically accumulated in inadequate surface storage facilities, glutted the market and resulted in tremendous economic losses. In addition to huge surface losses, the "wide open" production caused serious physical losses in the reservoir, resulting from the dissipation of natural energy and a poor understanding of physical laws governing reservoir behavior. Chaotic over-production in the early 1930's, bringing the industry perilously cloase to ruin, finally brought about laws to restore order and prevent further waste of natural resources. Some form of conservation law now exists in most important oil producing states.

An essential element in the prevention of waste is controlling the rate of production while maintaining sound recovery practices. "Wide open" production causes premature dissipation of reservoir energy leaving quantities of oil in the reservoir unrecovered. For this reason, the foremost requirement in conservation is that reservoirs be restricted to that rate of production which will permit the most efficient use of reservoir energy and result in maximum ultimate physical oil recovery.

Development of means to control waste proved to be a monumental legal and engineering task beset with many physical and economic obstacles. Since unilateral action of individual lease owners to restrict production would not deal adequately with the unit behavior of a reservoir and since

voluntary co-operative action has certain legal implications it was necessary that the power of state be used to effectively control production rates. The state, by the assumption of these powers, likewise assumed responsibility to attempt to protect the correlative rights of owners, which is the right of each owner to produce his fair share of oil for the market. Such control of production by enforcing an allocation of the quantity to be produced by each pool and within each pool by each lease or well is referred to as "proration."

It has already been pointed out that waste must be prevented above the ground as well as in the reservoir. In any estimate of what can be produced without incurring surface waste, consideration must be given to consumption and storage limitations. Proration is thus related to market demand.

B. Application of Proration at the Present Time

Nearly all of the important oil producing states have laws vesting their state regulatory bodies with authority to prescribe allowables or prorate production. While these state statutes define and prohibit waste and set up the necessary machinery for administering and enforcing conservation laws, national coordination is based on voluntary interstate co-operation through the aegis of the Interstate Oil Compact Commission. The Commission interprets market and production trends, periodically recommending to member states appropriate production quotas. A list of the states which are members of the Interstate Oil Compact Commission is contained in Appendix I.

States with effective proration laws such as Texas, Kansas and Oklahoma allocate production to various pools and to wells within a field by using allocation formulas. The American Petroleum Institute has recommended that such formulas be based upon acreage, bottom hole pressure, sand thickness, reserves, market demand, depth and maximum efficient rate of production (MER).[6] The formulas for allocation actually used vary from state to state. In some cases, formulas are also based on less desirable factors such as productivity index, number of wells, or potential.

For several reasons, proration has been applied to primary production only while stripper and fluid injection operations have been, in effect, exempt from restriction. Use of the power of state to restrict primary production was fundamentally justified on grounds of conserving natural resources. Restriction of "wide open" primary production came to be recognized as a necessity if maximum physical recovery was to be

attained. Also, it has been generally accepted that maximum recovery from water flooding was, in large measure, dependent upon the fastest continuous rate of production obtainable. Restriction of flood operations was thought to decrease ultimate recovery. Many stripper and flood operations produce at very low but still economically profitable rates. Therefore, it was thought that any restriction in such production rates might make the operation unprofitable and compel its abandonment, resulting in loss of oil that would otherwise have been produced. Since the purpose of conservation laws is to conserve resources, proration of water floods in such circumstances might have the opposite of the desired effect. Another reason for not prorating oil produced from water floods might be that the comparatively small quantity of oil produced from floods did not measurably decrease the allowable that could be assigned to primary production, in states having proration laws. Thus for years, there was relatively little interest in or demand for prorating water floods. The question of whether water flood production should be prorated has little significance to a particular state unless the state in question has (a) an effective proration law, (b) vigorous primary production which is being curtailed and (c) a comparatively significant oil production from water floods.

C. Why the Question of Prorating Water Floods Arises

An increasing amount of oil is being produced by water flood operations while the rate of discovery of new sources is declining. More and more reservoirs, depleted by primary means, are being converted to water flood. It is not surprising then that debate has commenced over the propriety and feasibility of prorating production from such floods. How such a debate came about involves the history of water flooding.

Early attempts at water flooding were probably made before 1900 at Bradford Field in Pennsylvania[7] but water injection was not legalized in that state until 1920. Pennsylvania is now almost totally dependent on water flooding for its oil production.[1] Water flooding as an oil producing process was well proved in both New York and Pennsylvania fields long before proration laws were introduced. However, since neither state has ever had a proration law, the question of prorating floods is academic in those states.

With the exception of short periods in Oklahoma and Kansas, proration has not, in effect, been applied to production from water floods in other states. Where an allowable has been set for water flood oil production, as in Texas, it has been on the basis of maximum producible quantities or on the basis of a fixed allowable which has been increased upon application.

Although the practice of water flooding was developed in the Bradford Field, the controversy over prorating water flood production has actually arisen in Texas where water flooding on a large scale is rather new, being initiated in 1949 and 1950 in the Permian Basin with the

Forrest Oil Company water flood.[8] In 1950, the Texas Railroad Commission had their first important hearing on exceeding the allowable for a water flood.[9] A policy of allowing water flood wells to produce at their maximum rate was established and held until August of 1955 when one of the major oil companies raised a challenge, which opens up the following questions:

Are new primary fields penalized unnecessarily by lower allowables to let water flooded wells flow freely?

Can restraints be placed on a water flood without damaging it and decreasing ultimate recovery, if controls are practical?

The future growth of water flooding will affect its competitive relation with primary production methods. As water floods produce a larger share of the oil, primary producers are sure to ask that proration be applied to such production.

II. A STATEMENT OF THE PROBLEM, LIMITATIONS OF SCOPE AND METHOD OF APPROACH

The resources of the nation as well as a number of subtle industry relationships are involved in the question of prorating water flood oil. Exempting water floods from allowables could be carried to a point that might decrease incentive for primary exploration. On the other hand, if prorating floods results in lower physical recovery or economic loss through attenuation of pay-out, many independent operators, relying on quick turnover, would be discouraged from developing projects which they would otherwise undertake. The net effect, either way, might be to decrease the nation's available reserves.

Both necessity and feasibility of prorating water flood oil production need to be examined. Up until the present time water flood oil production has not been regularly subjected to proration as has been primary production. With water flood production increasing in size and importance, demands are being made to have water flood oil included under production restraints. On the other hand, it is not clear whether a water flood operation can be curtailed without loss of ultimate physical recovery or economic loss through attenuation. While a great deal of theoretical work has been done on the physical principles involved in water flooding, there is frequently a lack of general agreement in the industry as to what flooding procedures will best insure maximum recovery. If some control must be exercised over flood production, various means of so doing have not been examined. Little has been written on the necessity

of prorating water flood production and nothing has been written which attempts to tie together both necessity and feasibility. Unless proration of water flood operations is both necessary and feasible, there is little practicality in restricting such operations.

This thesis deals with an important but none the less limited segment of the total question of prorating oil production from all types of secondary recovery. The limitations necessarily applied reduce the scope of the subject to manageable proportions. Water flooding is only a portion of all secondary recovery processes, but it is that portion which promises the greatest future growth. The second limitation applied is to the type of reservoir considered. This thesis deals with proration of water flood operations in sand or intergranular reservoirs which represent approximately two-thirds of all reservoirs.[10] This limitation to sand reservoirs permits examination of the question based on specific physical principles which apply only to that type of reservoir. The current debate in the industry centers largely on the question of prorating water flood production from such reservoirs. Sand reservoirs are the most universally susceptible to successful water flood operations. Also the theoretical development of precise physical principles governing flow through sand is further advanced so that the effect of flow variables can be ascertained rather definitively. In this manner it may be possible to reach reasonable conclusions as to the effect of curtailment on a water flood operation in such reservoirs.

Within these limitations, the purpose of this thesis is to define and investigate the issues involved in the current debate on the propriety of prorating water flood oil and to reach conclusions as to the

feasibility and probable necessity of prorating such production or to suggest alternatives where appropriate.

To do this an evaluation will be made of the future importance of water flood oil production in comparison to the total oil produced in the United States, in order to determine whether the necessity for prorating water flood production will likely become more acute with the passage of time. The physical factors affecting recovery of oil by water flooding will be reviewed in order to determine whether curtailment incident to proration will affect ultimate physical oil recovery from such floods. Available field evidence of the actual effects of curtailment will also be reviewed.

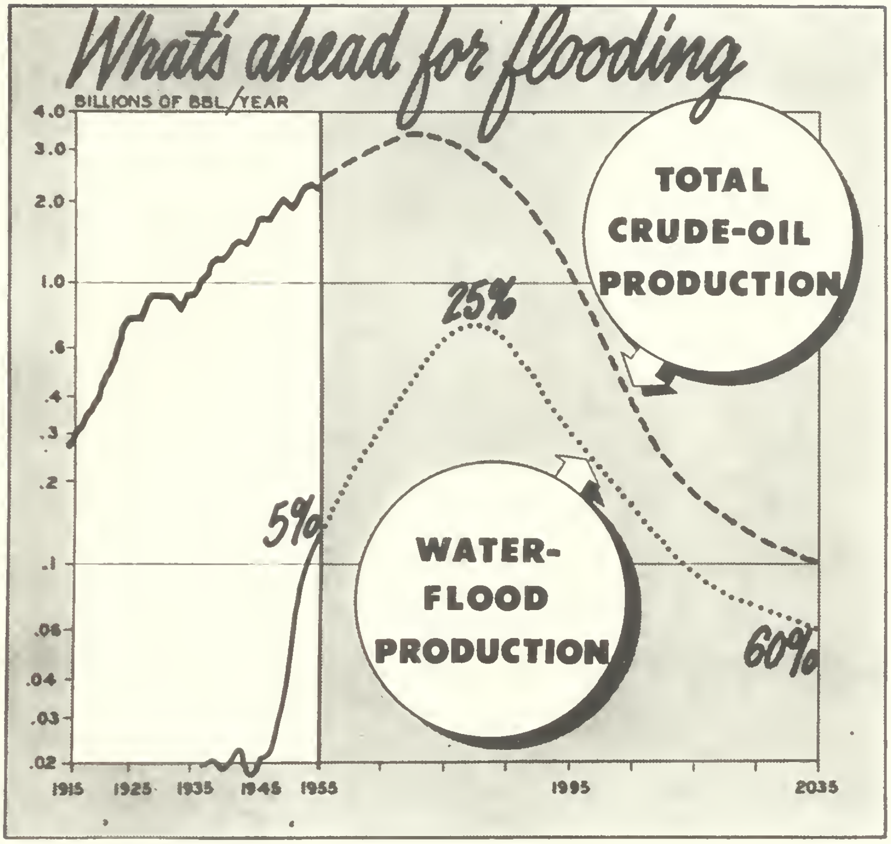
Much of the definition and investigation of the issues has been covered in the Introduction. A review of theory and practice will next be taken up, followed by a summary of the most important points, after which conclusions will be drawn.

III. THE PROBABLE NECESSITY FOR PRORATING WATER FLOOD OIL PRODUCTION

A. Current and Future Water Flood Oil Production

The question of prorating oil produced from water floods is still in the early stages of debate. Whether the debate becomes more or less acute will probably depend on the quantity of oil produced by future floods. Thus, an examination of the future of water flood production is essential in evaluating the question.

There has been a tremendous growth in water flooding operations in the past decade and the future promises much more. At a recent meeting of the North Texas Oil and Gas Association, A. E. Sweeney, Director, Secondary Recovery Division of the Interstate Oil Compact Commission, reported that although water flood production now constitutes only five per cent of the total United States production, it is expected to rise to an ultimate sixty per cent by the year 2035 as indicated in Figure 1.[11] He predicted that in 1980 water flood production will account for twenty-five per cent of the total United States production. Annual production from water floods has increased in the last four years from 80 million barrels to 130 million barrels representing an increase from 2.8 per cent of the total United States production in 1950 to more than five per cent during 1955. Water flood production of four important oil states in 1955 was reported as:



A forecast of water flood oil production as related to total crude oil production. From Sweeney, A.E.:"Water Flood Role Grows", Oil and Gas Journal, March 26, 1956

Figure 1.

State	Per Cent of Total Produced by Water Flood
Texas	3%
Oklahoma	14%
Kansas	12½%
Illinois	30%

The present and future relationship of total oil produced to that from water floods was summarized as follows:

	In Billions of Barrels	
	Total	Water Flood
Production, 1915-1954	50	1.2
Reserves, 1955	30	10.3
Future Discoveries	85	21.0
Production to Year 2035	165	32.5

Peak total oil production was estimated to occur in 1970, while peak water flood oil production will be reached in 1980.

From another source, the growth of water flood production from 1900 to 1953 is represented graphically by leading states in Figure 2.[12]

If such figures were published, a tabulation showing the ten states with the largest gross oil production, the portion produced by water flood and whether the state had proration laws would highlight areas where the question of proration of water floods is likely to become more acute with further development of water floods. The following table indicates the top ten states in 1955 United States production, the per cent of total production, and whether a proration law is in effect. The

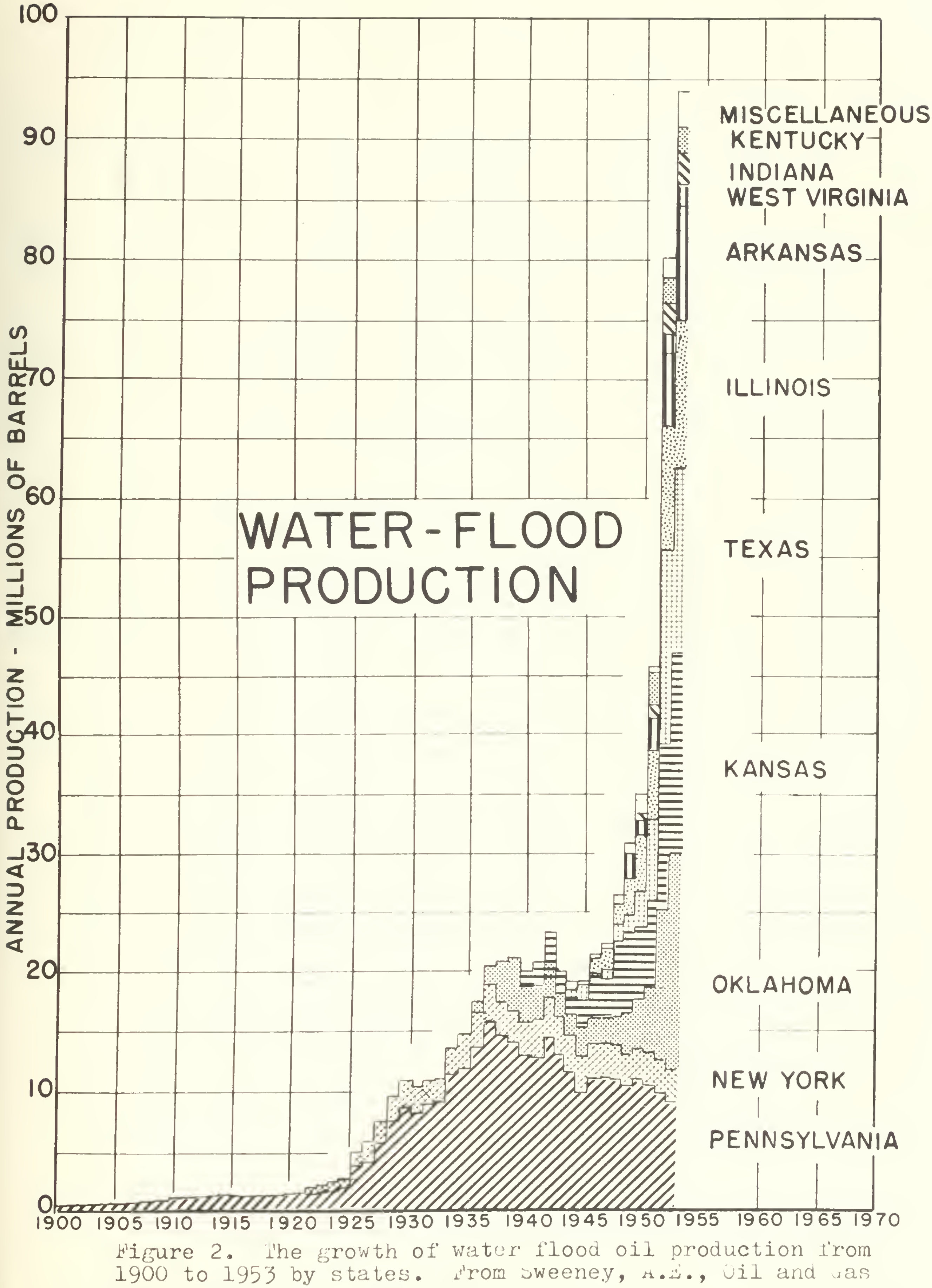


Figure 2. The growth of water flood oil production from 1900 to 1953 by states. From Sweeney, A.E., Oil and Gas Compact Bulletin, June 1955.

amount produced by water flood is not available.

Table 1

Rank	State	1955 Production[13] in Barrels	Per Cent of Total U.S. Production	Proration[4]
1	Texas*	1,051,567,000	42.52	yes
2	California	354,724,000	14.34	no
3	Louisiana*	267,314,000	10.81	yes
4	Oklahoma*	201,791,000	8.61	yes
5	Kansas*	121,661,000	4.92	yes
6	Wyoming	100,198,000	4.06	no
7	New Mexico*	81,778,000	3.31	yes
8	Illinois*	81,562,000	3.29	no
9	Colorado*	51,055,000	2.07	no
10	Mississippi*	37,317,000	1.51	no
	Others		4.56	

*Indicates member of the Interstate Oil Compact Commission.

Synthesis of the facts reflected in Sweeney's report,[12] the figures of Table 1, and the picture presented by Figure 2 sheds a little light on which areas are likely to become centers of debate on whether water floods should be prorated in the future. In Texas the question of prorating water floods is becoming acute because of the tremendous primary productive potential now restricted below MER and allowed to produce about 16 days a month. In California, water flooding has not expanded sufficiently to be a real factor and the state does not yet have a proration law. In Oklahoma and Kansas the question is potentially an active controversy. Water flooding is not yet significant in Louisiana

or Wyoming and the latter has no proration law. New Mexico floods are just getting underway. Illinois, Colorado and Mississippi do not have proration. This then is the approximate background on the ten states which produce more than 95% of the United States oil.

B. Basic Reasons for Growth in Water Flood Oil Production

There are good reasons for the tremendous growth of water flood operations. One of the most compelling is the increasing difficulty and expense in finding new oil reserves. In the ten year period, 1945-1954, wildcat wells drilled per year increased from 4,256 to 11,280. In 1945, 420 million barrels of reserves were discovered for an average of twenty-five barrels per foot of wildcat hole drilled. In 1954, 586 million barrels of reserves were added through new discoveries for an average of only eleven barrels per foot of wildcat drilled or less than one-half the return of 1945.[14]

Another important reason for the increase in water flooding is the fact that it represents less of a gamble than seeking primary production. It has been estimated, for example, that the Burbank Field will yield 140 million barrels of oil under water flooding. The American Petroleum Institute has estimated that the chance of discovering a new field with even a potential of 100 million barrels is one in 991 tries.[15] Water flooding is thus particularly attractive to the small operator who cannot afford an expensive exploration campaign.

In many cases the ultimate recovery with water flooding will exceed primary production alone by a ratio of as much as two or three to one. Primary production of the Bradford pool was estimated at 257,987,000 barrels while water flooding will produce an additional 305,909,000 barrels.[16] In a typical dissolved gas reservoir where primary recovery may approximate 21%, water flooding can raise this to 42% recovery. In a typical gas cap reservoir with primary recovery of 20%, water flooding

can raise recovery to 35%. Even in a water drive reservoir with a 60% primary recovery, water flooding may add another 10%.[14]

C. Other Factors Affecting the Necessity for Prorating Water Flood Oil Production

There are other factors which will affect the necessity for production restrictions in the future. Conservation of resources will certainly compel a continuance of production restriction necessary to insure maximum recovery. The need for extension of proration in the future will be affected, however, by the total power supply, the power demand and to some extent, by the international situation. The growth and application of other power sources such as atomic energy, synthetic or high energy fuels and hydroelectric development as well as future power requirements or consumption habits will determine the need for restricting production to market demand. Although prediction of such trends is beyond the scope of this thesis, the effect of their existence needs to be born in mind. Sweeney's estimates shown in Figure 1 presumably cover oil produced in the Continental United States and are not a forecast of future demand. If future demand continues to increase, it is evident that deficiencies in continental production will require increasingly larger imports. Whether such oil sources will be available in the face of rising foreign consumption is problematical. Also the possible results of rising nationalism may affect the availability of Middle East reserves. Another possible factor to be considered is whether some of the United States oil reserves will have to be eventually withheld from production as ready defense reserves. Such a decision would depend upon national strategy and national policy. These factors and perhaps many more should be considered in trying to evaluate future necessity for prorating water floods.

IV. THE FEASIBILITY OF PRORATING WATER FLOOD OIL PRODUCTION

A. Theoretical Indications and Laboratory Findings on the Effect of Curtailment on Ultimate Physical Recovery

If curtailment of production incident to prorating water floods did not lessen physical oil recovery, the question of prorating floods would be reduced to one of relatively simple economics. An examination of fundamental theory of fluid flow in a porous medium may indicate which factors are affected by curtailment. How they are affected may indicate what results can be expected from curtailment. After examining the generally accepted fundamentals, a further review of the literature in which there is apparent contradiction to these fundamentals may shed some light on the current debate of whether ultimate physical recovery is affected by curtailment. Finally, such a review of fundamentals should indicate which factors may be varied in order to bring about curtailment. The effects of varying such factors can then be examined in the light of field experience.

The principal development of fundamental theory of fluid flow in a porous medium has occurred in the last twenty years. Most of this theory is based on laboratory experiments with core samples. Wyckoff and Botset,[17] in flowing gas and oil through sand cores in 1936, first developed the relation of fluid flow to fluid saturation, using both a wetting phase fluid and a non-wetting phase fluid. They showed that the ability of a medium to permit a fluid to flow through it depended upon the saturation of that fluid in the porous medium and the ability of the

fluid to wet the porous surfaces of the medium. Buckley and Leverett[18] developed in 1942 a mathematical expression for the fraction of water flowing through a core which was saturated with water and oil and showed that the relative permeability ratio and the viscosity ratio determine the water fraction of fluid at any particular saturation. These ratios are the independent variables in Buckley and Leverett's simplified form of the fractional flow formula:

$$f_w = \frac{1}{1 + \frac{k_o \mu_w}{k_w \mu_o}}$$

where f_w = fraction of water in oil-water flow,

$\frac{k_o}{k_w}$ = relative permeability ratio of water to oil,

$\frac{\mu_w}{\mu_o}$ = viscosity ratio of water to oil.

It can be noted that since $\frac{\mu_w}{\mu_o}$ is a relatively constant value for the range encountered in a water flood operation, the $\frac{k_o}{k_w}$ ratio is essentially the single variable in determining what fraction of water, f_w, is contained in the flowing stream. Since the residual oil saturation can be computed graphically[18] from the curve $\frac{\partial f_w}{\partial \sigma_{\overline{w}}}$ versus water saturation, $\sigma_{\overline{w}}$, and since f_w is dependent on relative permeability in an actual flood, it becomes obvious that relative permeability is a very important factor. Following the graphical method of Pirson,[19] it can be seen that if other factors remain constant and the relative permeability is varied, f_w decreases with increases of $\frac{k_o}{k_w}$. The slope or derivative of f_w with respect to water saturation determines the oil saturation at water breakthrough and at the ultimate saturation.

In an investigation of all the factors which affect the performance of a linear flood, Rapoport and Leas[20] designed an extremely complex equation representing all possible variables, but found in a series of core flooding experiments that the nature of a flood could be evaluated by means of a simple scaling factor: $LV\mu_w$,

where L = total length of the flooded system (cm)

V = total flow rate/unit cross section = injection rate

μ_w = water viscosity

Rapoport and Leas concluded that to any reservoir material and any system of fluids (defined by its viscosity ratio, interfacial tension and contact angle) it is possible to assign a critical scaling coefficient ($LV\mu_w$) which will yield a maximum recovery. The net effect of their findings translated into flooding terms is that a critical flow rate exists for any particular flood. With injection below that rate, recovery will be diminished. Injection at a rate higher than the critical scaling coefficient would result in decreased efficiency or wasted energy since recovery is not further increased. In actual field conditions the critical rate is seldom reached because of limitations of overburden in pressure parting of the formation. The net applied result of Rapoport and Leas' work indicates simply that the highest rate of flooding possible under most conditions of overburden produces the greatest recovery. It is significant that Rapoport and Leas specified that a reservoir material and a system of fluids is defined by its viscosity ratio, interfacial tension and contact angle.

Continuing along the same line of investigation in 1955, Newcombe,

McGhee and Rzasa[21] studied the effects on oil recovery of the solid-water-oil contact angle, the oil-water interfacial tension, flood rate and oil viscosity. After devising ingenious means of varying some of these factors, it was found that:

> For both oil-wet and water-wet systems and a low viscosity oil, recoveries were functions of the oil-water interfacial tension; also increase in flood rate resulted in increased oil recoveries. High interfacial tension floods were more efficient than low interfacial tension floods on water wet systems, while low interfacial tension floods were more efficient on oil-wet systems. Intermediate or neutral wettability systems were less sensitive to rate of flood advance and interfacial tension than either oil-wet or water-wet systems. The effects of surface forces on oil recovery for high viscosity oils were not so well defined as for low viscosity oils.

There are several other papers which can be reconciled with the classical work of Rapoport and Leas[20] and Newcombe, et al.[21] Breston and Hughes[22] reported that higher flooding pressure gradients gave higher recoveries. Jones-Parra and Calhoun[23] validated Rapoport and Leas' findings with calculations based on Buckley and Leverett's formula.[18]

Although Rapoport and Leas[20] and Newcombe, McGhee and Rzasa[21] found that recovery in either water-wet or oil-wet sand was increased by increasing the flow rate, many others writing before them are not in agreement with these findings. For example, Pirson[19] states:

> The throughput rate will have an important bearing on the recovery; in a truly water-wet sand, a slow advance of the water front will favor the oil discharge ahead of the drive. In an oil wet sand, a faster water frontal rate should yield an oil recovery which will approach that expected from horizontal flooding in the absence of capillary and gravitational forces.

While Uren[24] writes the following on flooding rates:

> The rapidity with which a water drive is conducted may have an important influence upon the effectiveness with which residual oil is displaced. If the mineral surfaces of the reservoir rock are water wet, rapid flow of the flood water through the pore spaces will create a scavenging effect upon the oil particles. Hence recovery depends on the hydraulic effect of moving water. However, if the mineral surfaces are oil-wet, it is likely that higher recoveries would be secured with slower rates of production.

In 1943, Earlougher[25] concluded that there is a critical maximum velocity above which the oil recovery efficiency falls off very rapidly, based on laboratory flooding of core samples from northeastern Oklahoma water floods. In 1946, Morse and Yuster,[26] using sands not susceptible to commercial water flooding found that there was no effect created by flooding gradients or velocities upon residual oil saturation. In the same year, Calhoun, McCormick and Yuster[27] concluded that the crux of the problem of pressure gradient and recovery is wettability and that residual oil decreases with increase of pressure gradient. In 1948, Holmgren[28] reported that:

> For the range investigated the water input and resulting pressure gradient during a water drive at low gas saturation had no discernible effect on the final saturation.

In no case has there been a paper written since that of Rapoport and Leas of 1953[20] in which it has not been concluded that increased flow rates result in increased recovery. In several cases papers since then have confirmed and extended this fact. In many of these papers which cannot be reconciled with Rapoport and Leas there was no indication that the environmental conditions under which the experiments were conducted

such as wettability, interfacial tension or in some cases, viscosity, had been taken into consideration.

While there are numerous factors other than flow rate which affect oil recovery, they are for the most part either unchangeable or developmental in nature and are not affected by curtailment in such a way as to influence recovery. These include factors which are not subject to operator control such as sand thickness, areal extent, bed continuity, dip, fluid viscosity, effective porosity and permeability. These are inherent qualities of the reservoir unchangeably fixed by nature. There are also such factors as well spacing, flood pattern and effective well radius. These are subject to some control of the operator, but once set are not subject to much further variation. Some experiments have been attempted on changing the wettability of reservoirs.[29] The results indicate that no increase in oil recovery can be expected in water-wet sands. Although some increase is possible in oil-wet sands, the economic feasibility is not yet certain. Water quality is, of course, a factor of continuing concern to the operator and is subject to his control. It is not, however, necessarily affected by curtailment. The means of obtaining the optimum flooding results with respect to all of the above factors are adequately covered in the literature. The controversy over prorating water flood does not hinge on any of these factors. Curtailment does have some effect on flood pattern and this matter will be discussed later.

B. Field Experience with Flow Rates and Recovery

An examination of an engineering problem should be made in light of both theory and practice. Fundamental flow theory has been examined and it was found that recovery was generally thought to be increased by high flow rates, although there have been a number of findings which cannot be reconciled with the fundamentals. Field evidence of the effects of varying the flow rate on recovery will next be reviewed.

A search for unpublished field data on the effects of curtailment of a water flood was not very productive. There seems to be some reluctance in industry to release decline curve information. With reference to this situation one prominent authority wrote in a personal letter to the author:

> Actually the reason you have had difficulty in finding factual information on this subject has been due to a combination of factors, not the least of which is that some of those most influential prefer not to have such information a matter of record. (Cites example)

Occasionally a bit of information will appear in hearings before regulatory bodies. During the Kermit Field hearings before the Railroad Commission of Texas,[30] F. F. Wright of Sinclair Oil and Gas Company, cited an example of the deleterious effect of a field wide restriction in 1954 on the Olympic Pool, producing from the Senora Sand. This Senora Sand production was restricted to twenty barrels per day per well. He gave the following production figures:

		Production in Barrels Per Day	
1954	January	11,800	
	February	11,750	
	March	11,500	
	April	11,300	
	May	11,000	
	June	9,500	(first month of restriction)
	July	9,200	(second month of restriction)
	August	9,200	
	September	8,900	
	October	8,800	
	November	8,200	
	December	7,750	

To facilitate an evaluation of the effects of proration in this case, these figures have been plotted on semi-log axes in Figure 3a. The actual decline line is shown as a solid line while an estimated line, assuming no proration, is dotted in. The hatched area represents an approximation of the oil lost from the curtailment. One of the most significant features of this plot is that the restriction in June and July also caused losses extending into August and September.

From another source,[31] the total curve of this same flood was obtained and is reproduced here as Figure 3b. Just exactly what path the curve would have followed without restriction cannot be positively known. It could be argued, of course, that if a particularly productive stratum happened to water out at about the same time the restriction was imposed, the effect might be much the same.

There has been some hesitancy on the part of reservoir engineers to state unequivocally that high velocity of water flow will result in greater ultimate recovery although the use of high flow rates is generally advocated and the probability of greater resultant physical recovery is well confirmed. The improvement in recovery resulting from pressure gradient increases is much attested in the literature on field operations.

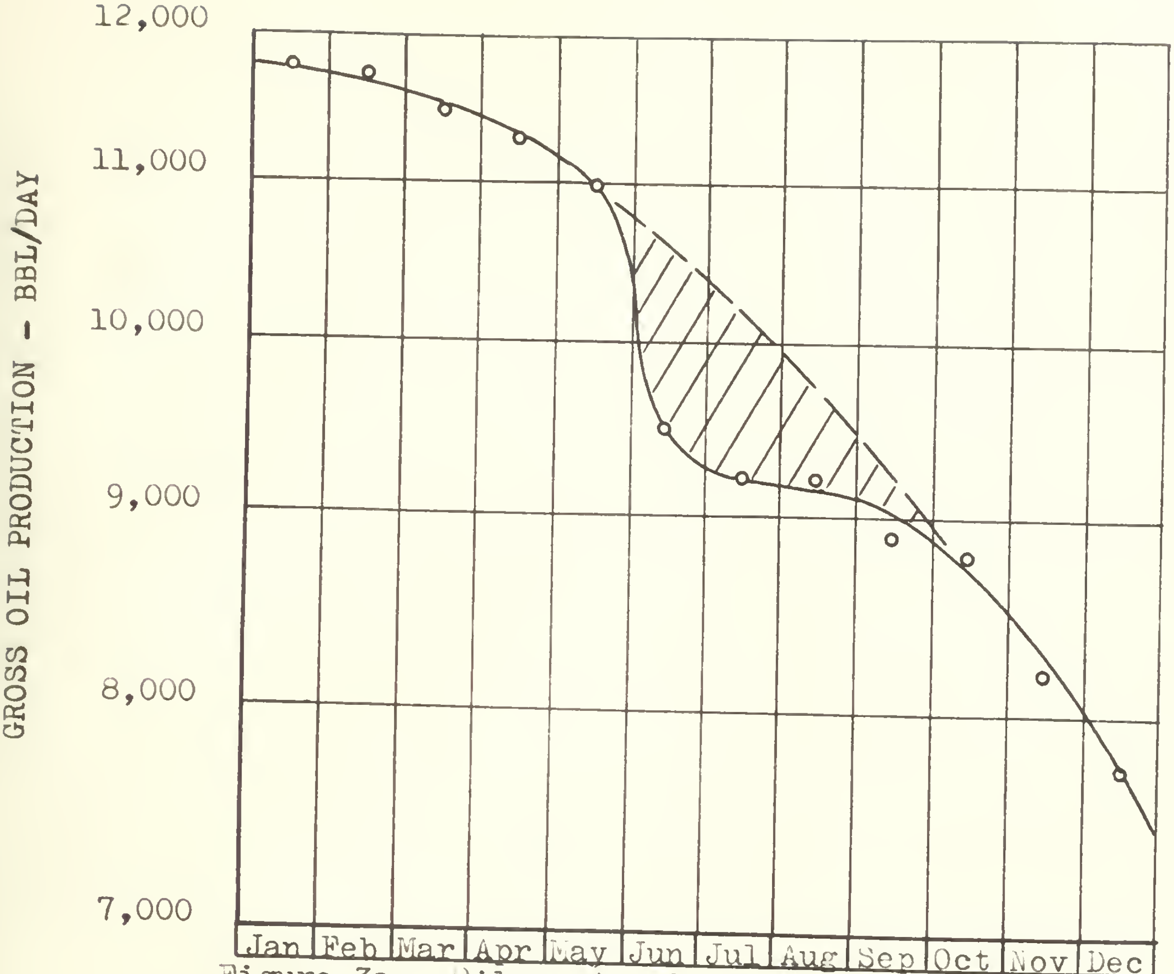


Figure 3a. Oil produced during a period of proration from the Olympic Pool in 1954.

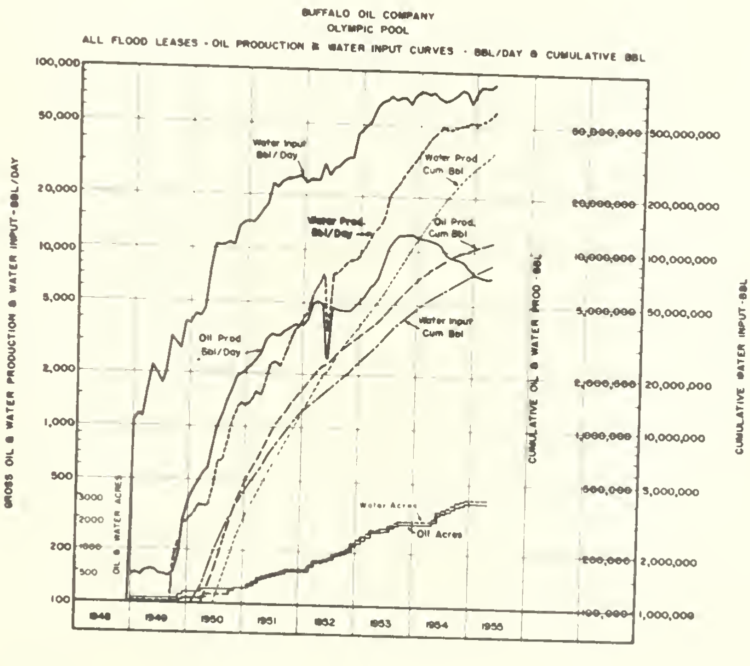


Figure 3b. Production curves on the Olympic Pool. From Earlougher, R.C. in the Oil and Gas Compact Bulletin, June, 1955

Conversely, decreases in flow rates have been observed to result in decreased oil production with the probability of reduced ultimate physical recovery of oil.

Dickey and Buckwalter[32] pointed out the advantages of increasing injection rates into water input wells, based on Bradford experience. Each of several increases of injection pressure was shown to result in increased oil produced. By extrapolating a production decline curve at the original pressure, the increased total recovery resulting from pressure increases was clearly indicated. Also discussed were possible economic gains from extending the time of abandonment, wider spacing, and possible savings in pumping. If these advantages accrue from increasing flow rates, it seems reasonable that decreases in flow rates required by proration would result in less oil production, earlier abandonment and greater operating cost.

Much of the interpretation of the effects of varying injection pressure and flow rates rests upon production decline curves. Ryder[33] has described the general use of decline curves and Buckwalter[34] demonstrated their application in evaluating water flood efficiency or estimating water flood production reserves.

In another well known paper, Ryder[35] reported that in four Bradford properties, each of eight increases in water pressure resulted in substantial increases in quantity of oil produced and prolonged the life of the flood. One of the best of Ryder's decline curves is reproduced here as Figure 4. Ryder concluded that the increased oil production came from flooding pores or sand layers not invaded at lower pressure gradients.

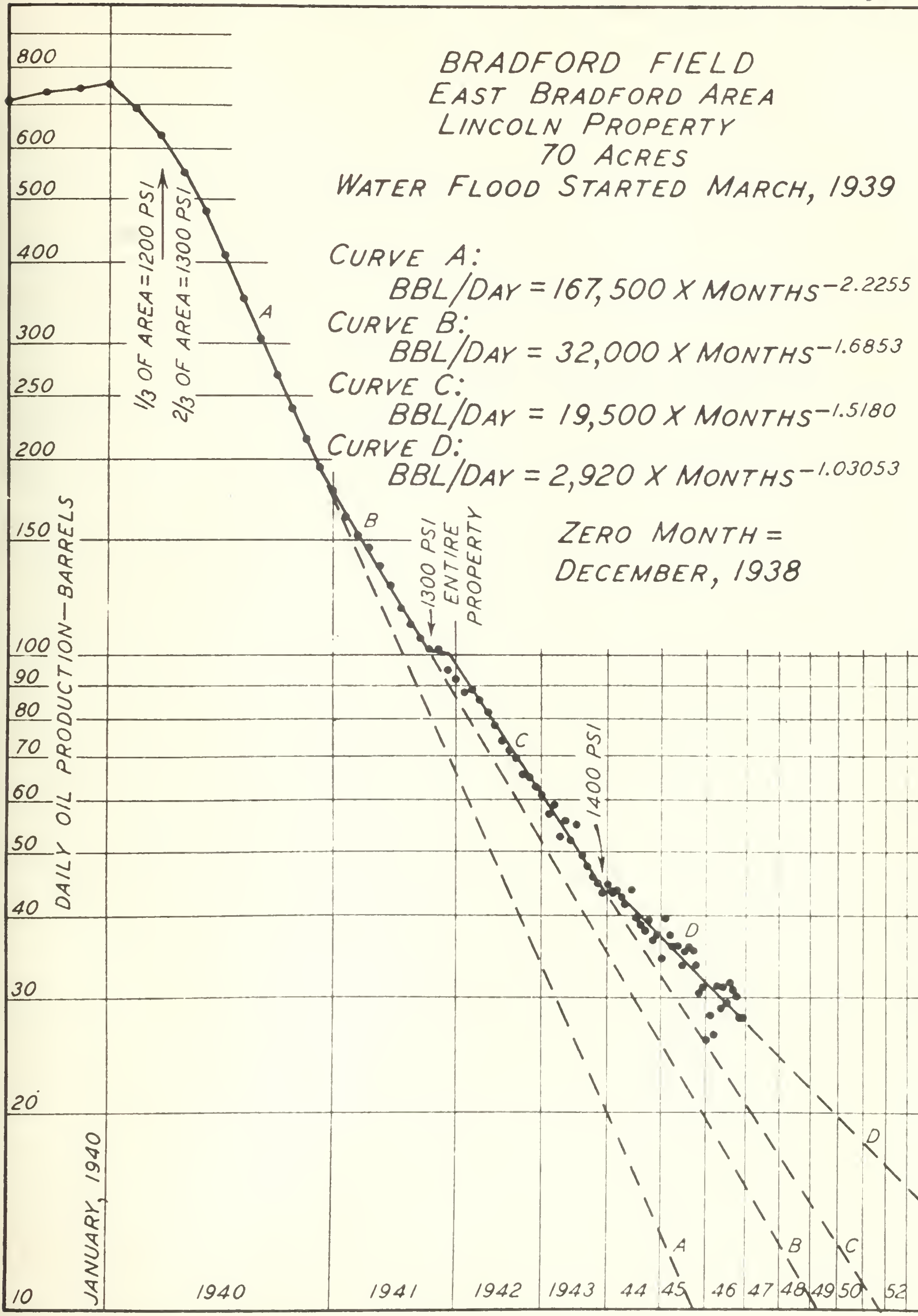


Figure 4. From Ryder, Producers Monthly, May 1947

In a paper written on procedures essential to maximum oil recovery from a water flood, Buckwalter[36] discussed the detrimental effect of a slow flood and demonstrated the point with numerous decline curves. He concludes that the most successful floods are in preferentially oil-wet reservoirs. For operations in the Bradford area, Buckwalter advocated high flow velocity and continuous operation.

Funk[37] reported results of proration in the mid-continent area. He interpreted several production decline curves and concluded that short periods of restriction may or may not hurt ultimate recovery depending on characteristics of the reservoir fluid and rock. He advocated that the established rate of input be maintained or possibly increased gradually through the life of a project to achieve a high oil recovery. In the cases cited the restrictions were short lived. It is interesting to note that Funk's paper is the first one reporting field experience on this question since the publication of the paper by Newcombe, McGhee and Rzasa[21] and that cognizance was taken of their findings in drawing conclusions on field data.

Whether curtailment has resulted in loss of recovery or just deferment is sometimes difficult to determine by examination of a decline curve. This is particularly true of brief periods of curtailment where the effect is not pronounced. The matter is judged entirely with reference to a hypothetical production line fixed by sight averaging. If the line is placed on one position it could indicate serious loss, if in another slightly different position, it might indicate little or no loss. Funk's Figure 3[37] shown here as Figure 5 illustrates the possibilities of this.

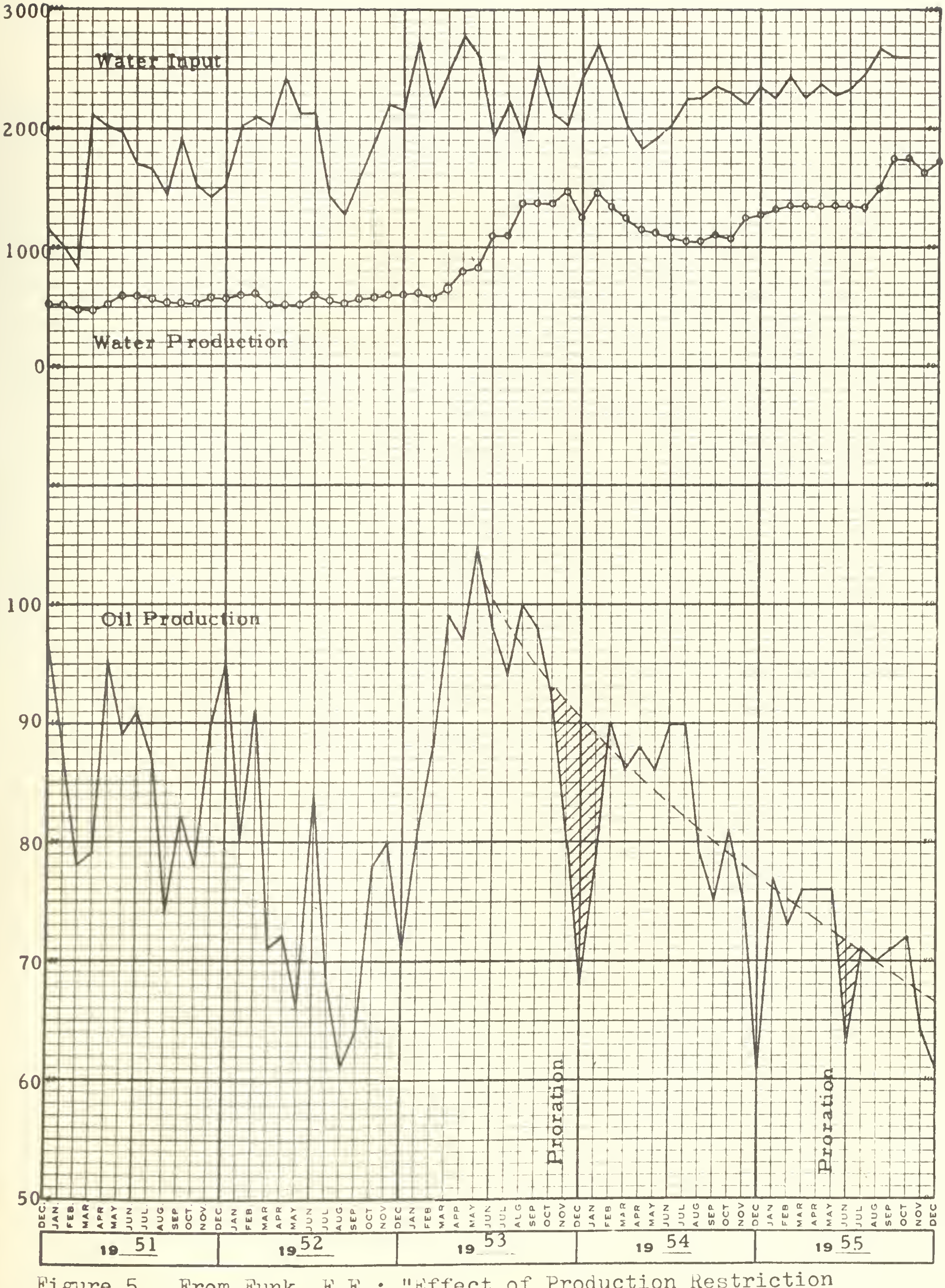


Figure 5. From Funk, E.E.: "Effect of Production Restriction on Water Flood Recovery", Producers Monthly, May, 1956

Little conclusive evidence exists to prove what has happened to such "lost oil" during curtailment. In an unbalanced pressure pattern, oil may drift away from the normal flow path and be lost to adjacent leases with lower pressures. Another possibility was raised by Funk[37] who concluded that gravitational segregation might also cause some loss of oil during curtailment when the oil bank would dissipate to some extent. There is also the possibility that although the oil which was "lost" during curtailment may ultimately be produced subsequent to the restricted period, the increment representing deferred production on the regular curve is so slight and so attenuated as to amount to an economic loss. In other words, the oil apparently lost may be recovered in such slight bits of production over such a long period as to be relatively valueless. The very width of the ink on the projected production line extended past the economic limit to infinity may represent restoration of considerable amount of "lost oil" but it is almost indistinguishable in present magnitude.

Attempts have been made to draw conclusions on the effects of curtailment from results of non-enforced shutdowns caused by labor strikes, river flood-outs or equipment failures. While interruptions usually give observable results, they are not necessarily representative of what might be expected from more carefully planned curtailment, nor are they representative of conditions during a period of prolonged production curtailment such as is presently applied to primary operations.

In summary, available field evidence on the effects of varying injection pressure and flow rate exists for both conditions where flow

is increased and where flow rate is decreased. In the former case, increased recovery is indicated. In the latter case, decreased recovery is indicated. Ryder,[34] while acknowledging that all laboratory findings are not in agreement, says this about the pressure gradient effects:

> No case of water pressure increase in the field without accompanying increase in the quantity of producible oil from sand so affected has ever come to the attention of the writer. In every case studied, more oil was removed from the sand when water-flooded at the higher pressure than could have been removed at the lower pressure. An increase in pressure somehow affects the quantity of oil removed and hence the quantity of oil remaining- the 'residual oil saturation'.

V. A POSSIBLE ALTERNATIVE METHOD OF CONTROLLING THE AMOUNT OF OIL PRODUCED FROM WATER FLOOD OPERATIONS WITHOUT CURTAILMENT

As indicated in the foregoing sections, proration of oil production from water floods implies either a decrease or an interruption in the flow rate. Most of the evidence in both experimental and field observations indicates that such curtailment most likely results in loss of ultimate physical recovery. If control of the total amount of oil produced from such floods is the objective, perhaps the end can be attained by other means.

The total number of flooding projects and the immense size of some of them indicate tremendous quantities of oil are potentially producible by this method.[15] There are over 700 projects in Texas and over 150 in Illinois. The immense Burbank water flood in Osage County, Oklahoma covering 18,000 acres will have a peak production of 20,000 barrels per day in 1964. Other projects will be even larger.

When these huge projects are fully developed, their output frequently equals or exceeds that of the reservoir's peak "flush" production. The production decline curves of primary and flood production frequently bear a striking similarity.[2]

The prediction of performance history of a water flood has been very successfully developed and provides a reliable means of anticipating production peaks. These techniques of flood analysis and evaluation are well covered in the literature.[38,39,40,41]

Unless some over-all planning or fortuitous timing occurs in the initiation of these huge flood projects, it seems almost inevitable that tremendous excesses of oil may develop either through the simultaneous peaking of several flood projects or simultaneous peaking of the floods during a period of high primary production. Under the worst conditions even drastically curtailing primary production may not prevent the consequences of temporary overproduction. Whether such tremendous stakes should be risked on the chance of fortuitous timing would seem questionable to say the least. Perhaps the answer lies in properly planning the total future production based on estimated productivity of approved water flood projects.

A possible way of doing this would be to have each applicant present an analysis of the future production performance of a projected flood when applying for approval of the project to the state regulatory body. After verifying this estimated performance profile or production curve, the regulatory body could then consult a cumulative production curve on all previously approved projects to determine the earliest and most advantageous date the new flood should commence. The new project would be fitted into the future total production picture in such a manner that its peak productive period would not unfavorably coincide with peak periods of other large floods.

Under such control, a proposed water flood project would not be approved for commencement until such time as its future productive capacity could be safely scheduled with minimum risk of resulting overproduction or need for drastic curtailment of primary operations. Under such circumstances the project operator would be assured of an opportunity to fully exploit the reservoir with no fear of curtailment or interruption

and consequent loss of ultimate recovery. The best time to settle the question of what rate of return an investor can expect is prior to committing on an investment. The flood operator needs reasonable assurance of what to expect in the way of regulation before making the tremendous investment required to develop a water flood operation. With such knowledge, the operator is encouraged to use whatever capital is required for maximum recovery. Faced with doubt over whether his operation will be prorated at some time during the life of the flood, a prudent man will provide for such a contingency by committing only as much capital as is justified by a lower assured recovery. The difference may mean a considerable loss in recoverable oil.

Many water floods are characterized by high lifting costs occasioned by the tremendous investment required to handle production with high water-oil ratio. Such operations exhibit a marginal dependence on stable production rate. Because of the high overhead, any curtailment in the production rate can render such an operation unprofitable and bring on financial insolvency. This seems particularly inequitable since the flood operation investment is usually based on a specifically computed pay-out time. Consequent bankruptcy and abandonment of an operation that would otherwise have been a continued producer results in a loss of oil which might be recovered under scheduled development as proposed.

Curtailment of primary production seems the best way of controlling such production, since it has never been shown that curtailment causes physical loss in such operations. In like manner, since controlled and scheduled development of water flood projects will prevent physical and economic losses, it seems the best method of controlling water flood oil production.

VI. SUMMARY AND CONCLUSIONS

As one of several conservation measures, proration was originally justified as a means of preventing waste, both above ground and beneath the ground. With minor exception, states having proration laws have applied restricted production allowables only to primary production. Water flood operations were not prorated because of the likelihood of causing a loss in recoverable oil and because the quantity involved did not appreciably decrease the allowables assigned to primary production. Although the percentage of oil produced by floods in Texas is relatively low the debate on whether water floods should be subject to proration arose in that state because of the rapid growth of water floods and the current severe curtailment of primary production.

Whether the question of prorating water flood oil will become more acute will depend on the necessity for and feasibility of such action. This thesis undertook a brief investigation of the most important factors bearing on the necessity and feasibility of prorating water flood oil production from reservoirs of intergranular porosity. If the current debate over the propriety of prorating oil from water floods is a fair gauge of the impact such production has on the total conservation structure, the future growth of water floods indicates that the question is one of growing concern to the industry. Estimates of oil to be produced from floods show that unless some change in production control is made, the oil produced from floods will likely compel even greater restraints to be enforced on primary production. This would probably produce inequities of great magnitude.

The future role of water floods was examined in the light of available statistics and forecasts. Although presently producing only five per cent of United States oil, it has been estimated that water floods will produce twenty-five per cent by 1980 and sixty per cent by the year 2035. The growth of water floods has been encouraged by the increasing difficulty and financial risk involved in finding new oil reserves. It is possible to produce as much or more oil from a reservoir by water flooding as was produced from primary production. Whether this prospective expansion of water floods will necessitate their proration may depend to some extent on the rate of development and use of other power sources. The impact of the future availability of foreign imports was also considered.

Since proration laws are based on preventing physical waste, the test of whether prorating water flood oil production is feasible depends on whether curtailment of flow will result in underground waste by loss of ultimate physical recovery. This question was examined both in the light of theory and practice. The consensus both in the laboratory and in the field indicates that proration of oil produced from water floods is not compatible with the fundamental purpose of conservation.

The fundamental theories of fluid flow and oil recovery were reviewed as reflected in the results of laboratory flow tests with core samples. The findings of Rapoport and Leas[20] indicate that recovery is a function of flow rate at the pressure gradients existing in the field. Although papers not in consonance with the findings of Rapoport and Leas[20] were written prior to their work in 1953, none which disagree substantially have been written since and several notable confirmations of their conclusions have since been published. These laboratory experiments indicate that recovery is increased in both oil-wet and water-wet sands by increased flow rates.

Because unpublished field data could not be obtained, the practical aspects of field experience with flow rates and recovery were examined in the published literature. Numerous examples of an indicated loss in recovery after curtailment can be found in the literature and no evidence from field observations indicated that recovery was unaffected by curtailment except for a few very brief interruptions. The use of decline curves for interpreting these effects was discussed and numerous papers were reviewed which showed that increased flow rates resulted in increased production and prolonged life for the flood, while decreased or interrupted flow rates appeared to result in loss of ultimate recovery.

Since some control of the amount of oil produced from water floods seems necessary and equitable and since curtailment of an operating flood is not feasible without risking loss of recovery, it is concluded that the industry should seek another solution to the problem. A method of attaining control without proration was discussed. This could be accomplished by controlling the initiation of floods. Once approved the flood would be permitted uninterrupted flow. Approval would depend on scheduling the total prospective capacity of the project so that its peak productive years would occur at a favorable period with respect to other anticipated production. To this end, restriction and control of the initiation of floods would permit planned control of such production without risking the waste of natural resources which seems probable if proration is applied to floods already in operation.

In addition to requiring efficient recovery practices, a well rounded petroleum conservation program in any important oil producing state should include provisions for proration of primary production and for the scheduled development of water floods. Such an approach would assure maximum ultimate

physical recovery with minimum probability of waste from overproduction. Unless controls properly suited to the appropriate production mechanism are used, the industry will be faced with either periodic excesses or inequitable curtailment practices. Well coordinated flood development coupled with reasonable proration of primary production will enhance ultimate recovery of oil in the United States, provide an equitable solution to production control problems, and lend stability to the future development of the industry.

physical recovery will enhance probability of its [illegible].
Unless controls properly suited to the [illegible]
are used, the industry will be faced with [illegible]
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with reasonable provisions for pressure [illegible]
recovery of oil in the United States, [illegible]
production control problems, and [illegible]
of the industry.

APPENDIX I

LIST OF MEMBER STATES AND ASSOCIATES OF THE INTERSTATE OIL COMPACT COMMISSION

Members	Associates
Alabama	Alaska
Arkansas	Arizona
Colorado	Georgia
Florida	Nevada
Illinois	Oregon
Indiana	Washington
Kansas	
Kentucky	
Louisiana	
Michigan	
Mississippi	
Montana	
Nebraska	
New Mexico	
New York	
North Dakota	
Ohio	
Oklahoma	
Pennsylvania	
Tennessee	
Texas	
West Virginia	

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49